Chapter 3
Energy Consumption and Energy Sources on Planet Earth

3.1 Definition of Energy and Units for Energy and Power

Energy, while an abstract concept, is well-defined in physics and science. Unfortunately the word "energy" has been stolen by psychologists and others to describe a mental state: "he/she has lots of energy", or "I can transfer energy through my hands to you". This sounds like energy is something mysterious and fleeting. But this is *not* the energy considered here. As taught in every high-school, it takes kinetic energy for something to move. This energy of movement can be acquired by release and conversion of stored-up (potential) energy. Without physical energy and energy conversions, the whole Universe would be dead and we would not exist. Since we will be discussing energy usage, exchanges, and supplies, it is necessary we first define a unit of energy. For example how many units of energy are in a liter or gallon of petrol.

The word "energy" comes from the Greek meaning "inherent work". Although others before him had hinted at the conservation of mechanical work and heat, it was Sir James Prescott Joule (1818–1889) who first carefully measured and proved the inter-convertibility of heat and mechanical work, firmly establishing the abstract concept of energy and conservation of energy. He developed calibrated thermometers and reproducible means of measuring temperature and heat energy. After quantifying energy he proved that a certain amount of heat energy can be converted to produce a certain amount of mechanical motion energy and showed that a big wagon needs more energy to be moved than a small one in proportion to its weight.

The laws of energy conservation and energy conversion are the cornerstones of physics. One can define energy on the microscopic as well as macroscopic scale. Microscopic atoms, molecules, electrons, protons, neutrons, nuclei, photons are all endowed with energy, in addition to mass, charge, etc. Likewise cars and trucks moving over a highway possess mechanical kinetic energy, acquired by converting petrol-fueled heat of combustion in their engines into mechanical motion of their wheels and thence onto their vehicle. People who drive cars can visualize energy best by equating it with liters or gallons of petrol. They know their car needs 60 L or 16 gal of petrol to fill their tank to allow them to drive 600 km or 373 miles.

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In technical parlance, the chemical energy contained in 60 L (16 gal) of petrol when liberated as heat of combustion, is converted by the engine to mechanical energy of wheel rotation, taking the car a distance of 600 km (373 miles). Thus one can equate 1 L of petrol energy with 10 km of mechanical work, or 1 gal (3.8 L) to move an average 2005-model car 23 miles (1 mile = 1.6 km).

Energy can be in the form of kinetic energy, e.g. a falling stone, or potential energy, e.g. a stone on the edge of a cliff ready to fall, one being convertible into the other. Chemical energy stored in molecules like petrol, and nuclear energy present in atomic nuclei, are both forms of potential energy that can be converted into kinetic energy under certain conditions. Heat is the total kinetic energy from swarms of chaotically moving or vibrating molecules or atoms. Heated molecules in a gas can be directed to push a piston, thereby converting heat into mechanical energy of motion. When hydro-carbon (C_mH_n) molecules in petrol react with heated atmospheric oxygen (O_2) in a combustion engine, C, H, and O atoms are rearranged into new molecular compounds (CO_2 and H_2O) with liberation of kinetic energy in the form of heated gases that move pistons. Similarly a neutron flying into the nucleus of a uranium atom, can cause a re-arrangement of protons and neutrons in the nucleus (Chapter 6). This results in the splitting (fissioning) of a uranium nucleus into two halves and liberation of kinetic energy imparted to the two recoiling fission fragments which generate heat in the solid that embeds them. The amount of energy liberated in the fission of a nucleus is generally ten million times larger than that liberated in a chemical reaction. This is the reason why a nuclear plant can produce so much more power from a kilogram of nuclear fuel (uranium), than a coal- or oil-fired power plant can generate from a kilogram of petro-chemical fuel.

The physicist's unit of energy is aptly called the Joule, abbreviated J. Power is defined as the energy delivered per unit time or the energy *rate*. In physics, the standard unit of power is the Watt (W) or Joule per second (J/s). That is, 1 W = 1 J/s. Comparing energy with water, one can liken power to the cups of water that pour out of a faucet per unit time, and energy to the number of collected cups of water. The antiquated "horsepower" (HP) unit, originally based on the strength of horses, is still used to rate car engines. It equals 746 W, that is 1 HP = 746 W = 746 J/s. Historic definitions of various other units for energy and power can be found in physics textbooks. For example the calorie energy unit which is still used, is based on heating 1 g of water by 1°C (Celsius) measured by a thermometer, and equals 4.2 J (1 cal = 4.2 J). For multiples of a basic unit, one uses k for kilo (thousand or 10^3), M for mega (million or 10^6), G for giga (billion or 10^9), and T for tera (trillion or 10^{12}). Thus 1 kW = 1,000 W of power, 1 MW is 1 million watts of power, etc. A peculiar energy unit is the kWh or kilowatt-hour which is disguised as if it is a power unit. It actually is an energy unit and represents energy delivered at a rate of 1 kW = 1,000 W = 1,000 J/s for a period of 1 h = 3,600 s. Thus 1 kWh = 1,000 (J/s) × 3,600 (s/h) = 3.6 million J = 3.6 MJ.

In dealing with large quantities of energy, three commonly used units are the Giga-Joule = 1 GJ = 1 billion Joule; the MegaWatt-hour = 1 MWh = 1 million Watts for 1 h; and the MBTU = 1 million BTU (British Thermal Unit) = 1.055 GJ.

Another "super-unit" used in the English system is the quad = 10^{15} BTU = 10^9 MBTU. They are related as shown in Brief 4. Conversion factors are needed so that one can compare published data from different energy sources that use different units. While calories, BTUs, and kilowatt-hours will probably stay around for a while, to avoid confusion we shall use (and get used to) mostly modern units of Joules and Watts for energy and power in this book. A senseless unit often used in newspaper reports is MegaWatt-hours per year to give the output of a power plant for example. Mentioning "for a year" is often omitted but implied. Here one oscillates from using power units MW (= MJ/s), converting to energy units MWh = 3,600 MJ, and then back to power again: 1 MWh/year = 3,600 MJ/8,760 = 0.41 MW.

Besides units, in comparing amounts of energy generated from a kilogram of oil, coal, or uranium, it is important to specify whether the energy is in the form of heat, electricity, or mechanical motion. We follow the convention of placing (e) or (m) in parentheses after units of energy for the latter two; otherwise it is assumed to be heat. Often the parentheses are omitted. Thus 1 GJ(e) ≡ 1 GJe designates electric energy, while 1 GJ is a quantity of heat energy. The distinction is important because electrical and mechanical energy are of a higher grade than heat. That is, electrical and mechanical energy are more adapt at carrying out man-desired tasks. Most of man's energy usage involves mechanical motion or electricity, which is obtained by conversion of heat energy via a steam or gas turbine/engine, or by direct conversion of electrochemical energy into electricity. The laws of thermodynamics reveal that only 30–40% of gaseous heat (= chaotic molecular motion in all spatial directions) can be converted via a turbine or combustion engine into uni-directional macroscopic mechanical motion by turbine wheels or pistons and via dynamos into electricity.[1] In such energy conversions, high-temperature heat carried by a gas or steam enters an engine or turbine and after performing mechanical work, is transferred at a lower exhaust temperature to a coolant that dumps the left-over heat content to air or water. This heat dump can be a cooling tower or heat exchanger using water from a pond, river, lake, or ocean. Conversion of chemical energy directly into electricity in fuel-cells and the subsequent production of mechanical motion via an electric motor is more efficient than conversion of heat. It takes place with overall efficiencies of 55–85%. In evaluating world energy resources, published fuel supplies are usually listed by mass or volume and density, whose energy content is given as latent heats of chemical combustion. On the other hand hydro, wind, or solar energy sources specify electric outputs. In comparing these energy forms, we shall assume a coarse conversion factor of 33% for conversion of heat into electricity, while for electrochemical conversions we shall assume efficiencies of 55%. For inter-conversions of mechanical and electric energy we shall assume ~100% (Brief 4).

[1]The "second law of thermodynamics" states that the maximum mechanical energy extractable from heat is given by the Carnot fraction $(T_1 - T_2)/T_1$, where T_1 and T_2 are the inlet and outlet turbine/engine absolute temperatures in K or R.

ENERGY:

1 GJ = 10^9 J = 0.278 MWh = 278 kWh = 9.48 x 10^5 BTU = 0.948 MBTU
1 MWh = 1000 kWh = 3.6 GJ = 3.413 x 10^6 BTU = 3.413 MBTU
1 MBTU = 10^6 BTU = 1.055 GJ = 0.293 MWh = 293 kWh
1 Quad = 10^{15} BTU = 1.055x10^9 GJ

POWER:

1 GJ/y = 31.71 J/s = 31.71 W = 0.03171 kW
1 W = 1 J/s = 3.6 kJ/h = 31.54 MJ/y (1 y = 3.154 x 10^7 s)
1 kW = 1 kJ/s = 3.6 MJ/h = 31.54 GJ/y

CONVERSION OF HEAT ENERGY TO ELECTRICAL OR MECHANICAL ENERGY:

3 GJ ~ 1 GJ(e) ~ 1 GJ(m); 3 MWh ~ 1 MWh(e) ~ 1 MWh(m)
3 MBTU ~ 1 MBTU(e) ~ 1MBTU(m)

AUTOMOBILE FUEL REQUIRED FOR INTERNAL COMBUSTION ENGINES TO GIVE 600 km (373 mi) RANGE, CONSUMING 2.2 GJ ~ 0.72 GJ(m) OF ENERGY:

One "tankful" petrol ≈ 45 kg petrol ≈ 60 liters (16 gal) of liquid petrol

One "tankful" alcohol ≈ 82 kg C_2H_5OH ≈ 107 liters (28 gal) of liquid alcohol

One "tankful" ammonia ≈ 98 kg NH_3 ≈ 163 liters (43 gal) of liquid ammonia @ 12 atm

One "tankful" methane ≈ 42 kg CH_4 ≈ 60 liters (16 gal) of compressed CH_4 gas @ 67 atm

AUTOMOBILE FUEL REQUIRED FOR FUEL-CELL ENGINES TO GIVE RANGE OF 600 km (373 mi), CONSUMING 1.3 GJ ~ 0.72 GJ(m) OF ENERGY:

One "tankful" hydrogen ≈ 10 kg H_2 ≈ 143 liters (38 gal) liquid hydrogen @ T = 20 ^oK , or
≈ 600 liters (160 gal) compressed hydrogen gas @ 245 atm

One "tankful" ammonia ≈ 58 kg NH_3 ≈ 97 liters (26 gal) of liquid ammonia @ 12 atm

NOTE: (e) = (electrical) ; (m) = (mechanical)

Brief 4 Units and conversion factors for energy and power

It is helpful to recall here that a tankful of petrol in a medium-sized automobile contains about 60 L (16 US gal). This contains 2.2 GJ of chemical combustion energy which can be converted to mechanical motion to propel the car an average distance of approximately 600 km (373 miles). Conversely 1 GJ of heat energy is stored in 27 L (7.3 gal) of petrol which moves a car 273 km (170 miles). Brief 4 lists the approximate equivalences for automobile propulsion and travel using petrol, alcohol, ammonia, methane, and hydrogen fuels. The heats of combustion in ICEs are assumed to be convertible to mechanical energy by a factor of 0.33, while the efficiencies of FCEs are assumed to be 0.55 in Brief 4. Ammonia, hydrogen, and bio-alcohols may become the main fuels of the future for automotive fuel-cells and combustion engines (Chapter 5).

3.2 Amounts and Forms of Energy Consumed by Man

According to statistics supplied by the US Census Bureau and Department of Energy (DOE), there were 281,422,000 people living in the USA in 2000, who consumed a total of 1.18×10^{11} GJ/year of heat-equivalent energy from the primary energy sources listed in Brief 5. The US consumption rate was thus 419 GJ/year = 13.3 kW or 4.4 kWe per person. This compares with a total world consumption of 4.01×10^{11} GJ/year of heat energy by 6,157,401,000 people or 67 GJ/year (0.71 kWe) per person in 2000. These per-capita consumption figures might indicate that a US resident is consuming six times the world average. However a lot of hardware (cars, planes, ships, bridges, tractors, etc.) is used in non-US countries but were fabricated in the USA. So some of the energy for their manufacture must be allocated to non-US residents. This increases the 67 GJ/year figure and decreases the US figure of 419 GJ/year. These considerations apply primarily to Asia, Africa, and South-America who buy such hardware in exchange for labor-intensive (non-petrol-consuming) goods, oil, and raw materials. Europe and Japan, like the USA, also make energy-consuming hardware products traded throughout the world. Without considering detailed balances of world trade and energy exchanges, coarse estimates change the above figures for the year 2000 to about 73 GJ/year or 0.77 kWe per person for the world and about 300 GJ/year or 3.2 kWe per US citizen, still four times the world average.

Energy Resource	Annual Quantity Consumed	Equivalent Heat Consumption	Percentage
Oil	7.08×10^9 barrels/y	4.0×10^{10} GJ/y	33.90%
Natgas (Natural Gas)	2.38×10^{13} cu.ft/y	2.5×10^{10} GJ/y	21.18%
Coal	1.70×10^9 tons/y	3.74×10^{10} GJ/y	31.68%
Uranium[1]	20,000 tons/y[1]	0.85×10^{10} GJ/y[1]	7.20%
Hydroelectric[2]	-------------	0.33×10^{10} GJ/y	2.80%
Geothermal[2]	-------------	0.034×10^{10} GJ/y	0.28%
Wood/Bio, Wind, Solar[3]	-------------	0.35×10^{10} GJ/y	2.96%
TOTAL:		11.80×10^{10} GJ/y	100%

NOTES: [1]With present U-235 "burners", only 0.5% of the intrinsic uranium energy is utilized. With U-238 breeder reactors, only 400 tons/y would be needed to provide 0.85×10^{10} GJ/y; [2]Hydro and geothermal are close to the maximum available in the USA; [3]Bio-fuels, wind, and solar may expand ten-fold in the next twenty years but most likely will never provide more than 15% of total energy needs.

Brief 5 Annual energy resource consumption in the USA in year 2000

Although the numbers in Brief 5 apply to the year 2000, numbers for 2008 have not changed much except that wood/bio, wind and solar energy have seen a 100% increase approximately, raising their year-averaged contribution from 2.69% to about 5.4% of total consumption. Energy conservation such as home insulation, improved auto mileage, etc., have balanced the increases in energy use due to US population growth to 300 million in 2008. In the next 20 years non-US energy consumption will increase, particularly in China. Global consumption rates are approximately five times the US rates listed in Brief 5. They are estimated to reach 123 GJ/year = 3.9 kW = 1.3 kWe per person when averaged over two decades from 2005 to 2025 with a world population of 6.1 billion in 2000 nearing a plateau of 7.8–8 billion predicted for 2025. These figures forecast a world energy consumption rate totaling 0.86 trillion (10^{12}) GJ per year averaged over the next 20 years. With total primary energy reserves as listed in Brief 6, one then calculates depletion times of 16.4 years for oil, 18.4 years for natural gas, 153 years for coal, and 1,100 years for uranium, *assuming* all needed heat-equivalent energy is supplied *only* by oil, or *only* by natgas, or *only* by coal, or *only* by uranium. Exploitation of 1.5 trillion barrels of oil from shale and tar-sands, and 10 quadrillion cubic feet of natgas from sea-beds, requiring less than 50% of contained fuel energy for recovery, are included. If tar-sand oil and sea-bed natgas are excluded, only one trillion barrels of oil and five quadrillion cubic feet of natgas are left, and depletion periods change to 7 years for oil and 6.5 years for natgas. Of course it is unrealistic to assume that *only* oil, *only* natgas, *only* coal, or *only* uranium will be used to support *all* of man's energy needs. Nevertheless these calculated solitary depletion periods are useful to indicate the relative mortality of these resources, showing uranium and thorium's superior long lives as energy sources.

Resource	Quantity	Heat Content	Conversion Factor	Depletion Time @ 123 GJ/y per man (Popul'n = 7×10^9)
Oil (including tar-sands)	2.5×10^{12} barrels	1.41×10^{13} GJ	5.65 GJ/barrel	16.4 years
Natgas (including sea-bed hydrates)	1.5×10^{16} cu.ft	1.58×10^{13} GJ	1.05 GJ per 1000 cu.ft	18.4 years
Coal	6×10^{12} tons	1.32×10^{14} GJ	22 GJ/ton	153 years
Uranium	1.1×10^{7} tons ($^{235}U + {}^{238}U$)	8.60×10^{14} GJ ($^{235}U + {}^{239}Pu$)	8.6×10^{7} GJ/ton	1100 years
Thorium	3×10^{7} tons	2.87×10^{15} GJ (^{233}U)	8.6×10^{7} GJ/ton	3330 years
TOTAL:		3.89×10^{15} GJ		

NOTES: Depletion times assume all mankind's energy needs are provided by one resource only.
1 barrel = 42 gallons = 159 liters; 1 gallon = 3.785 liter; 1 cu ft = 28,316 cm^3 = 28.316 liters;
1 ft = 30.48 cm; 1 mile = 1.609 km; 1 lbs = 0.454 kg; 1 (short) ton = 2000 lbs = 907.19 kg;
1 (metric) ton = 1000 kg = 2204.62 lbs; 1 year = 365 days = 8,760 hours = 525,600 min = 3.154×10^7 sec.

Brief 6 Estimated world reserves of prime energy resources in 2005

In the real world, the transportation sector which comprises our vast fleets of land, air, and sea vehicles, consumes most of the available oil. In the USA, this amounts to about 35% of all energy consumption, but world-wide the percentage for transportation is closer to 40% with the balance of 60% mostly electricity, since less energy for heavy industry is used. At 3.44×10^{11} GJ/year, the actual availability of petrol beyond the year 2005 would then be 24 years without tar-sands oil, and 41 years with tar-sands oil included.

While locomotion of most transportation vehicles is obtained via petrol-burning combustion engines, electricity is generated by means of steam or gas turbines that utilize heat obtained from coal, uranium, or natgas. Additional small quantities of electric energy are provided by geothermal sources, hydro-turbines, wind-turbines, and solar cells. To extend the epoch of the well-developed petrol-burning combustion engine, natgas can be compressed or liquefied and used in place of petrol for cars. In the 1970s when the price of petrol skyrocketed during the oil embargo, many automobilists started using LPG (liquified petroleum gas), which is mostly compressed propane and butane (at ~10 atm) extracted from natgas in Pennsylvania, Siberia, and elsewhere. Compressed methane gas (at ~120 atm) also became popular when that fuel became less expensive than petrol. In the US oilfields, the percentage of methane (CH_4) in natgas varies from about 68% in Pennsylvania to 96% in mid-continent. The balance is a mixture of the higher alkanes in progressively smaller amounts: ethane (C_2H_6 ~30%), propane (C_3H_8 ~8%), and butane (C_4H_{10} ~2%). Thus compressed or liquefied natgas can be substituted for petrol to propel automobiles when oil becomes scarce and expensive. For this reason, it would be prudent to preserve natgas for near-future use as a portable fuel and not burn it up for electric power generation. The latter can easily be run on coal and uranium alone. If we assume that all of the presently available five quadrillion cubic feet of natgas (*not* including speculative retrieval of methane-hydrate from sea-beds) will be available for fueling our transport vehicles in addition to 2.5 trillion barrels of oil, the period for continued use of fossil-fueled combustion engines might be extended. Instead of 41 years, it then would take 56 years to exhaust fossil fuels. This is with the proviso that oil and natgas are used *only* for vehicle fuels, and electricity is produced *only* by coal, uranium, and renewables. Under this scenario, more time is available to develop new propulsion systems and synfuels for aircraft, ships, and long-haul land transport. Many believe the above time estimates are too optimistic and that most probably the out-of-oil time-point will be reached in 40 years and the out-of-natgas time-point in 50 years after 2010.

If burning coal and natgas in electric power plants were to be halted to reduce global warming and to conserve them as raw materials for making plastics,[2] one finds that present nuclear power generation must be expanded fourfold to replace fossil-fueled power plants. For the USA, this means that 300 new uranium-burning plants must be added to the existing 104 operating nuclear power plants as soon as possible. However to replace fossil fuel energy used in transportation, a further

[2] The word "plastics" is used here to include organics, hydrocarbons, carbon nanotubes, fibers, and all materials or products presently derived from petrochemicals.

expansion of nuclear power plants from 400 to 800 units of 1,200 MWe each would have to be in place by 2050. Additional supplies of nuclear electricity must accommodate vast fleets of new electric plug-in automobiles and the manufacture of portable synfuels. The portable synfuels are essential for running new propulsion systems of long-haul transport vehicles (e.g. aircraft) when they can no longer use petrol or natgas. Prior to total oil depletion, severe oil shortages can be expected to develop well before mid-century, as production from different oil fields are reduced or halted (prices increased!) when they are approaching exhaustion. It is estimated this will happen in about 20 years! Though it is impossible to set a precise date, we believe *we will see few petrol-driven cars after 2030.* As indicated in Brief 5, electricity from "renewables" (hydro, geothermal, wind, solar, bio-mass) helps. But for them to produce enough portable synfuels for the world's vast fleets of long-haul transport vehicles would be far too costly compared to nuclear generation (Chapter 4). To field eight hundred new nuclear power plants in the US by 2050 is nearly impossible unless a WW-II-like concerted effort is undertaken; in WW-II the US was able to build more than 10,000 aircraft per year. A mis-informed government, manipulated by anti-nuclear advocates who believe all energy needs can be handled by "renewables", will probably impede such a development until serious (avoidable) power shortages and brown-outs make their appearance. By then it is too late to implement a full nuclear power rescue program. The more likely scenario is that 300 new nuclear plants will be running by 2050, and that several hundred coal-burning air-polluting power plants will continue to operate till the end of the twenty-first century until they can be replaced with nuclear plants (Chapter 9).

In the manufacture of portable synfuels there are of course losses in converting prime heat or electricity into chemical energy of a synfuel. As shown in Chapter 5, synthesizing hydrogen, ammonia, or hydrazine from air and water can be done with an energy conversion efficiency between 10% and 60%. That is, 40–90% of prime energy is lost in converting it into portable synfuel energy. As long as there is an abundant source of prime energy (uranium or coal), this poses no problem. Even if it would take 10 GJ of prime energy to make 1 GJ of synfuel energy, there is no bottleneck. To a traveling automobilist, portable synfuel energy is more valuable than non-portable nuclear reactor heat. He does not mind if a substantial amount of the original nuclear heat used for chemical synthesis is lost, just like he is quite willing to waste 70% of the heat produced in his internal combustion engine as long as the balance of 30% is converted so as to move his vehicle. On the other hand if the only source of prime energy is biomass-generated alcohol, and it takes more alcohol fuel to grow alcohol fuel (due to running of farm equipment, distillation process, etc.), the situation would be unsustainable in a no-oil, no-coal, no-uranium future. Only with uranium-generated electricity or heat to provide base-load energy needed for cultivating and harvesting plants and to extract their alcohol, can bio-alcohol become a practical synfuel by converting non-portable nuclear energy into a portable fuel.

Electricity is one of the greatest gifts to mankind allowing him to communicate by telephone, radio, television, and to have all the comforts of a modern home such as electric lighting, air-conditioning, refrigerators, heating, cooking, etc. Without electricity we would have candles and torches for lighting, cold water for bathing, spoiling food, and swelter in hot dwellings during summer. Instant communications

around the world would also be impossible. It is very fortunate that nature has provided us with very light negative electrons that can pass swiftly through metal conductors such as copper. If electrons would have been heavy (with the same mass as positive protons), there never could have been readily available inexpensive electricity as we know it. Because of the properties of electrons, electric power can be delivered rapidly and distributed widely with minor propagation losses, to the great benefit of man. The same comment applies to uranium fission which allows the entire world to have at least a thousand years of electric energy and more than 3,000 years when breeding thorium is included (Chapter 6). In the early days of electric power, protesters tried to block its distribution, claiming that thousands of people would die if high-voltage AC power lines would be stretched out over the land. In 1811–1816, a body of laborers in England protested the introduction of labor-saving machinery. Led by Ned Lud these "luddites" rioted and set fire to factories. Similar self-damaging protests are made by today's anti-nuclear technophobes or "neo-luddites" who try to impede the expansion of nuclear power. They are probably unaware that their goals coincide with those of terrorists who wish to destroy Western civilization. Senator Robert Kennedy once observed that in almost every national issue "One-fifth of the people are always against," and that the contrarians are quite bull-headed. Philosophically one can argue whether electricity and nuclear power are a blessing or curse to man. It is up to man to use these gifts of nature for good or evil. One hopes destructive uses can be rooted out and all of mankind will band together to enjoy the benefits of ample uranium-generated electricity for millennia.

3.3 A Brief History of Energy

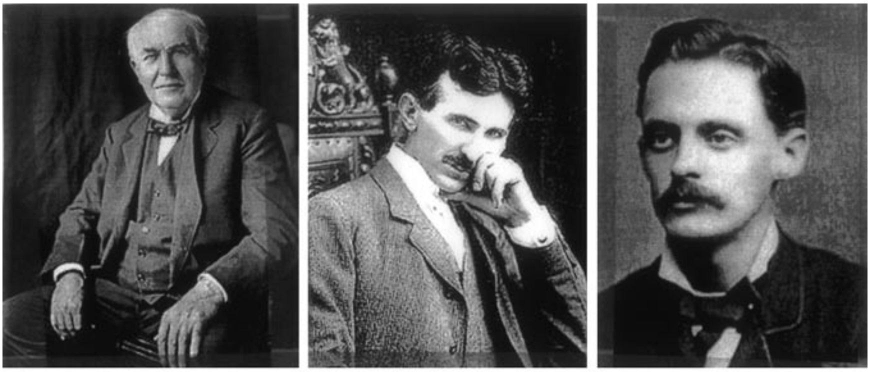
In 1650, the world was populated by 550 million people, or less than 10% of the present population. Besides sunshine which energizes agriculture, controllable energy resources available to man were:

Human Labor (via contracts, indenture, slavery, or prisoners to build structures, roads, etc.).
Animal Labor (horses, donkeys, camels, elephants, dogs, for transporting people and goods).
Wood, Oils, and Coal (burned for lighting, cooking, heating, melting/forging copper and iron).
Wind (windmills grinding wheat, pumping water; sailing ships transporting goods and people).
Water Flow (waterwheels grinding wheat, aquaducts, drainages, etc.).

These main forms of energy were all utilized in one way or another to satisfy man's basic needs and wants for water, food, warmth (heat), housing; or for manufacture of goods such as clothes, candles, furniture, saddles, carriages, ships, armor, weapons for hunting, defense, and warfare, etc.; or for moving people and goods (transportation). They are still available, but now we have six billion people.

In the eighteenth, nineteenth, and early twentieth century, several discoveries and inventions were made that profoundly changed the world's energy picture. First came the steam engine, originally demonstrated by James Watt of Scotland in 1770. It burned coal that heated water in a boiler, converting it into steam which in turn pushed pistons that turned wheels. It was actually preceded by an "atmospheric pump" that used condensing steam to pull a vacuum for suction, invented in 1712 by Englishman Thomas Newcomen, to pump water out of flooded mines. However it was not until 1807, after engineer Robert Fulton (USA) made improvements in the mechanical linkages and conversion cycle of heat to mechanical motion, that steam-ships and steam-locomotives were developed worldwide. Starting in the 1820s, steamships plowed the oceans and big rivers of the world, while trains pulled by steam-locomotives traveled over railroad networks all over the globe, connecting widely separated land-locked territories. Coal became a very important commodity and many new coal mines were opened to feed the hungry steam engines of the 1800s. Some coal-fueled steam-powered automobiles were also built, but only the rich could afford them.

Probably the three most prolific inventors who developed electric power and its many applications were Thomas Alva Edison (1847–1931), Nikola Tesla (1856–1943), and Elihu Thomson (1853–1937), shown in Brief 7. Edison was born in the USA in Milan, Ohio, while Tesla's birthplace was Smiljan, Lika, in the former Austro-Hungarian province of Croatia, and Thomson (founder of General Electric) was born in England but grew up in Lynn, Massachusetts. Edison started his career as a telegrapher and after improving telegraph equipment, became almost instantly famous for inventing the phonograph in 1877. After that, he made numerous additional inventions such as the incandescent light-bulb and the motion picture camera, acquiring over 1,000 patents. He started one of the first industrial research labs in Menlo Park, New Jersey. Tesla came to the United States in 1884, after studying physics, mathematics, and electricity at the Realschule in Karlstadt in 1873, the Polytechnic Institute in Graz, Austria, and at the University of Prague. He began work as an electrical engineer with a telephone company in Budapest in 1881, then joined Continental Edison Company in Paris where he designed dynamos. Wile in Strassbourg in 1883 he conceived of the AC (= alternating current) induction motor. But he was unable to interest anyone in Europe to develop his invention. So he decided to go to work for Edison directly in Menlo Park, where he set out to improve dynamos. Tesla got a letter of recommendation to give to Edison from Charles Batchelor who wrote: "I know two great men (who understand electricity). One is you and the other is this young man" (Ref. I-5). However when Tesla tried to convince Edison of introducing AC instead of DC (= direct current) electricity on power lines to run electric motors and other equipment, Edison refused to listen to him. Edison had little faith in mathematics and physics taught in his days and presumably wanted to protect his capital investments in all the DC electrical apparatus and facilities he had built. Tesla then left Edison and after a brief interlude while he filed for AC motor patents, he gave lectures on electricity. In 1888 Tesla presented a famous lecture on AC motors and transformers at the American Institute of Electrical Engineers (now IEEE) which moved industrialist George Westinghouse to buy Tesla's patents and to ask Tesla to work for him.



Thomas Alva Edison (1847-1931) | **Nikola Tesla** (1856-1943) | **Elihu Thomson** (1853-1937)

Brief 7 Pioneers of electric power development and its applications

Although Edison was a brilliant inventor and businessman, he had a stubborn streak. He held on to defending the use of DC electricity and combated Tesla's and Thomson's innovative AC electric power generation by declaring that AC power distribution was extremely dangerous and should be banned. Elihu Thomson, founder of General Electric, had also become convinced that generation and distribution of AC electric power was superior to DC. Between 1885 and 1892, Thomson and Tesla invented several versions of today's ubiquitous AC electric induction motors as well as gaseous electric discharge lights (neon) and other products run by AC electricity. AC voltages are much easier converted and boosted and AC power distribution over copper wires is less lossy than Thomas Edison's DC electricity which powered the street-lights of New York in the 1890s. That is in general, AC power can be delivered more efficiently over large distances than DC power at voltages between 1,000 and 100,000 V. George Westinghouse who was now financing Tesla's work, built and exhibited the first commercial hydroelectric turbo-generator at the 1893 World Fair in Chicago and in 1895 completed the first Tesla-designed hydroelectric plant powered by waterfall-driven turbines at Niagara Falls. It delivered a "whopping" 1.1 MW(e) of electric power that ran the lights and streetcars of Buffalo, NY, 26 miles away. General Electric built the first power lines for this venture. In 1880, Elihu Thomson who taught science and his colleague Edwin Houston had started a company in Philadelphia called Thomson-Houston to sell arc lamps. Later they developed fog-piercing signal equipment using radio-waves just discovered by Heinrich Rudolf Hertz. In 1892, financier John Pierpont Morgan merged Thomson-Houston and Edison General into General Electric making it the biggest manufacturer of electric lighting in the world.

The invention of a coal-burning steam-driven turbine by Sir Charles Parsons in England in 1884 provided an alternative to the waterfall-driven turbines used in hydroelectric power plants. In Parson's scheme, a boiler heated by burning coal converts water to pressurized steam which in turn drives a turbine that can generate electricity. Steam turbines are now the major generators of electricity and coal is

the prime energy source for 52% of all electric power generation in the USA, as it is similarly worldwide. Only 5% comes from hydro-electric power plants since the use of most rivers in the USA suitable for dams and large-scale electric power generation has been exhausted. In the US, additional steam-turbine electricity is now (2009) generated by heat from uranium fission (21%), and by burning natural gas (12%), petroleum/oil (3%), or industrial waste such as wood, biomass, alcohol (3%). Geothermal steam, wind-power, and solar-cells provide the remaining 4%.

Two additional world-changing developments were the introduction of the petrol-fueled internal combustion engine for automobiles in 1889 made by Gottfried Daimler in Germany, and the flight of a petrol-engine-powered airplane in 1904 by Orville and Wilbur Wright. Mass-production of autos in 1908 by Henry Ford in the USA, and selling his cars on the installment plan, were another two revolutionary steps that changed the world. After 1908, mass-produced petrol-powered cars overtook steam automobiles and horse-drawn carriages, while many coal-burning locomotive and steamship engines were replaced by diesel engines. The rapid expansion of automobile usage and aviation, with increased demands for petroleum, created today's large oil companies which recover, refine, and distribute enormous quantities of refined oil for a worldwide market.

In the Middle East, underground sources of oil were known to exist for centuries and exploited to provide fuel for oil-burning lamps and stoves. When it appeared that oil could power automobiles, William D'Arcey, an Australian businessman, obtained a 60-year concession in 1901 to drill and extract oil from 500,000 square miles or five sixths of what is now Iran (Ref. I-3). He formed the Anglo-Persian Oil Co, later to become Anglo-Iranian and still later British Petroleum (BP). Similarly, in 1904 in what is now Iraq, the Armenian C.S. Gulbenkian recognized the enormous potential of oil and persuaded the Turkish Sultan Abdul Hamid to transfer ownership of immense tracts of land from the Ministry of Mines to private ownership (mostly himself), establishing the Iraq Petroleum Co. Later on, BP and Royal Dutch Shell obtained contracts to exploit the oil fields in Iran, Iraq, and Arabia and to export the oil. US companies Exxon and Mobil, which had their starts in the oil fields of Pennsylvania, Texas, and California, entered the Middle East arena in 1928, when they became part owners of the Iraq Petroleum Company. Gulf, Standard Oil of California (Chevron), and Texaco got involved somewhat later. Control over the Middle East oil fields stayed firmly in the hands of these "seven sisters" until 1973, when host governments demanded more control and revenue from their mineral and petroleum wealth. Today the oil-producing nations of the world have united under OPEC (= Organization of Petroleum Exporting Countries) which regulates the world's oil production rates and prices.

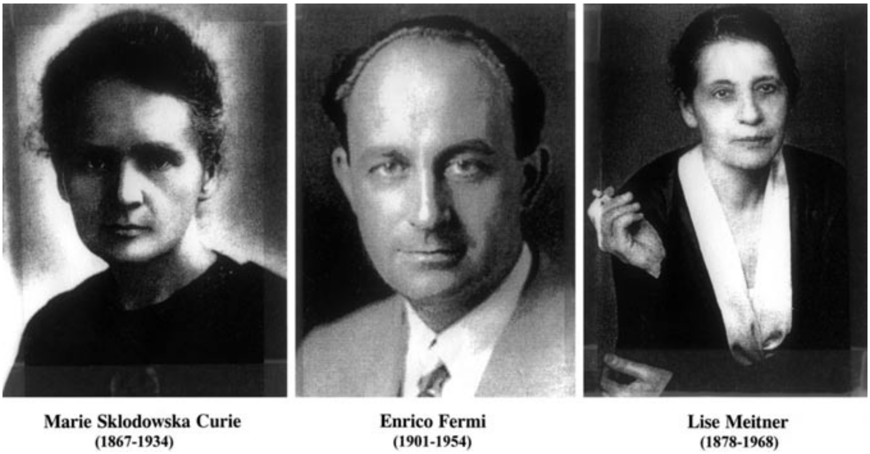
In summary, two energy sources already known in the middle ages but previously consumed in only modest amounts, were suddenly catapulted into major world commodities, namely:

Coal – experiencing a large increase in demand after 1820 to empower steam engines; and after 1900 to vaporize water for electricity-generating steam turbines.
Oil – expanding enormously after 1901 to fuel automobile combustion engines.

Today's oil consumption continues to rise, driven by ever expanding fleets of petrol-burning transport vehicles and craft, while the continuously expanding use of coal is due to increasing demands for electricity. Oil has allowed mankind to transport goods and people all over the world quickly and affordably, while electric power enabled man to develop many new manufacturing techniques, products, and services. Electricity provides modern homes with light, heat, cooling, electric stoves, refrigerators, radios, televisions, telephone service, etc. Increased use and availability of oil and coal has also promoted world population growth and a desire in the less developed countries to acquire modern comforts. Oil and coal consumption rates have thereby reached a level where depletion of oil is forecast to occur in a few decades (one generation), while coal is expected to last only one century if world demand continues to rise at the present rate and no alternatives are introduced. Without oil, it is impossible to maintain current forms of transportation, and without trucks and airplanes it is not feasible to produce and distribute enough food to feed the six billion people that are presently on our planet. Fortunately, nuclear fission was discovered in 1939, and sufficient extractable uranium and thorium has been found on earth to generate all the needed electricity for manufacturing portable fuels for the entire world for the next 3,000 years. It appears that divine intervention wanted man to discover this new energy source in time to avert a human catastrophe when oil runs out.

One of the first scientists to analyze the large amounts of energy locked up in the nuclei of heavy atoms as revealed by nuclear decay and emissions of particles, was Madame Marie Curie (Brief 8). She was born in Poland in 1867 as Maria Salomea Sklodowska. After self-studies of mathematics and physics under difficult circumstances in her native Poland due to the occupation of Poland by Russia, Maria went to Paris where she obtained degrees in science (1893) and in mathematics (1894) at the Sorbonne as one of only two and one of only five women. She met Pierre Curie at the university and married him in 1895. Professor Pierre Curie was an expert in the physics of magnetism as well as a superb instrument designer, and Madame Curie had joined him in his lab as his assistant. They heard of a curious observation by Henri Becquerel that a photographic plate left totally in the dark together with some uranium salt showed images normally only produced by exposure to the sun. Marie decided to find out what caused it and started with some pitchblende which contained uranium. Using Pierre's special instruments and her expertise at separating chemicals as a physical chemist, she discovered that thorium in the pitchblende was also radioactive as well as the uranium, and that still other elements in the mineral were even more radioactive when separated and concentrated. One of those elements she named polonium after her native Poland and another radium. After 3 years of tedious work, she managed to isolate radium which became a standard for research on nuclear emanations and nuclear physics research. In 1903, Pierre and Marie Curie as well as Henri Becquerel received the Nobel Prize for their discovery of the new radioactive elements. Madam Curie discovered that the nuclei of some heavy atoms decayed while emitting three different particles which were labeled α, β, and γ (alpha, beta, and gamma). However in 1903, the make-up of a nucleus and an explanation of that decay was still a mystery. One had deduced earlier that the nucleus of an atom contained

protons and that these nuclei were surrounded by electrons to make the atom neutral. It took the 1932 discovery of neutrons by Chadwick in England before a satisfactory picture of nuclei filled with protons and neutrons could be formulated. It explained many previously puzzling observations about radioactive decay but it was too late for Madame Curie to get involved. She died in 1934. However Marie Curie's daughter, Irene Joliot-Curie (1897–1956) who followed in her mother's footsteps to become a radiochemist, did participate in unraveling the mysteries of nuclei. In 1935, Fred Joliot and Irene Curie received the Nobel Prize for their discovery of the artificial induction of radioactivity in aluminum when bombarded with high-energy alpha particles (Ref. II-21).



Brief 8 Discoverers of uranium radioactivity and fission

Having learned that some elements can be made radioactive by bombardment with high-energy nuclear particles, it did not take long before artificial neutron-induced fissioning of uranium was discovered. The history of this discovery is very interesting and full of intrigue. Some of the following information is from Richard Rhodes' fascinating book (Ref. I-6). In Italy in the mid-1930s, Enrico Fermi (Brief 8) was bombarding uranium with newly discovered neutrons, and observed that neutrons (atomic mass M = 1) were absorbed by uranium (atomic mass M = 238),[3] causing the latter to transmute into new product elements with different atomic mass. Based on

[3]A nucleus is made up of Z protons and M − Z neutrons. Each of the Z protons has unit atomic mass and unit charge. They determine the total positive charge of a nucleus; hence Z is also called the atomic charge number. The neutron mass is almost the same as the proton mass but has no electric charge. The total number of "nucleons" is the sum of protons and neutrons in a nucleus and is called the atomic mass number M. A given element has a fixed number of protons Z, but can have different "isotopes" with different numbers of neutrons and thus different mass number M. Uranium's most abundant isotope is U-238 with M = 238 and Z = 92, i.e. 92 protons and 146 neutrons, while fissionable U-235 has 92 protons and 143 neutrons.

previous research, it was believed that atomic masses of new transmuted elements had to either gain 1 amu or lose 1–4 units from the original atomic mass M = 238 of uranium. But he found that many product atoms did not have the expected chemical properties of such transmuted species with say M = 239 and Z = 92 and instead found some species with what appeared to be M ~ 95. In Dahlem, Germany, at the Kaiser Wilhelm Institute (KWI), Otto Hahn, Lise Meitner, and student Fritz Strassman decided to redo Fermi's reported experiments. Like Fermi, they also found products with for example M = 144 and Z = 56, disagreeing totally with prevailing theory.

While Hahn and Meitner were pondering this result, Hitler invaded Austria in 1938 and incorporated it into Germany. Lise Meitner who was Austrian, faced new ugly Nazi laws that suddenly applied to her. She learned that her government-funded contract with KWI was about to be canceled because she was part Jewish, in spite of pleas by her colleagues. With the help of Dutch physicist Dirk Coster who picked her up in Dahlem, she went on a train to Holland and fled Germany. From Holland she went to Niels Bohr's institute in Copenhagen, Denmark for a brief rest before going on to Stockholm, Sweden to work with Karl Siegbahn, a renowned researcher of nuclear phenomena. In December 1938, Meitner got a letter from Hahn telling her he had repeated the experiments with neutron bombardment of uranium. He wrote that after careful chemical analysis of the products, he and Strassman found one product was definitely barium with Z = 56, *not at all* close to Z = 92. Did she have any ideas how to explain that?

Meitner (Brief 8) met with her nephew Otto Frisch during Christmas 1938 in Sweden, and discussed Hahn's letter with him. After expressing skepticism but still preoccupied with Hahn's observation of barium, Meitner suddenly remembered a statement by Niels Bohr that he believed the nucleus of an atom such as uranium was like a pulsating liquid drop. They then conceived of the possibility that a nucleus could split in two halves during a drop-stretching waist-producing pulsation after absorption of a neutron. They estimated this could happen if the atomic charge number exceeded Z ~ 90 because of repulsion between the two halves, each half being filled with many positively charged protons. Uranium with Z = 92 protons, was close to this value. The two "fission" products should each have atomic charge numbers whose sum was close to 92. That is if barium with $Z_1 = 56$ was one product, the charge number of the other fission product had to be near $Z_2 = 36$ if protons were to be conserved. Fissioning uranium actually yields product atoms with Z_1 and Z_2 spread over a range of values rather than one particular set and the proton sum $Z_1 + Z_2 \approx 92$ does not quite hold as we know now (Section 6.2.1). Additional calculations convinced Meitner and Frisch that their hypothesis was physically plausible. They also determined that the liberated energy had to be enormous: ~200 MeV per fission or 82 GJ per gm of U-235 which according to Brief 4 equals ~40 tankfuls of petrol per gm U-235. This also equals about 0.94 MW-day of released heat energy per fissioned gram of U-235 in a power reactor or 1 MW delivered all year long by a steadily fissioning 384 g (0.85 lb) of U-235.

Frisch who worked at Bohr's institute in Copenhagen returned to Denmark right after the Christmas 1938 visit with his aunt in Sweden. He told Niels Bohr what he and Lise Meitner had deduced from the data of Hahn and Strassman. Bohr himself

had proposed the liquid-drop model for a nucleus, and immediately concurred with their conclusion, stating this was a very important discovery. Next, Frisch put together an experiment using an ion chamber he had in his lab. On January 13, 1939 he found that the masses M of some products from neutron-bombarded uranium atoms detected by the chamber, were much larger than the usually observed protons ($M = 1$, $Z = 1$) or helium ions ($M = 4$, $Z = 2$). They had indeed values of about half the mass of a uranium atom ($M = 238$). This was experimental proof that neutron-bombarded uranium can fission. Niels Bohr had left by boat to lecture at Princeton, USA, where he informed his colleagues about the Meitner-Frisch findings on January 17, 1939, after receiving a telegram from Meitner. One of these colleagues was Enrico Fermi who had just arrived in New York on January 2, 1939 after returning from Stockholm where he had received the Nobel Prize for his pioneering work with neutrons. Fermi had decided not to return to fascist Italy under Mussolini, because his wife was Jewish and faced persecution.

The splitting uranium story told by Bohr was quickly passed around by the small US "nuclear club". Within two weeks, experiments with ion chambers were conducted at the National Bureau of Standards, which confirmed the astounding observations by Frisch. Shortly thereafter, Einstein wrote a letter to President Roosevelt warning him Hitler might develop a super weapon using uranium fission. Thence the secret US Manhattan Project was born. To prove that uranium fission could work on a macroscopic scale, Fermi designed and built the first nuclear reactor at the University of Chicago, which went "critical" on December 2, 1942. Next, in an incredibly short 2 years, plutonium production reactors were erected at Hanford, Washington, and a gigantic gaseous diffusion plant was built at Oak Ridge, Tennesee, to separate fissionable U-235 isotopes from natural uranium (0.7% U-235, 99.3% U-238). At Los Alamos, New Mexico, a team of the brightest scientists in the world under the leadership of Robert Oppenheimer worked feverishly to develop a nuclear bomb, thinking Hitler might be ahead of them. After testing the first bomb at Alamogordo, N.M. on July 16, 1945, WW-II was ended with the detonation of two additional nuclear weapons, one on August 6, 1945 at Hiroshima, and the other on August 9, 1945 at Nagasaki, Japan. The irony is, that the three fascist-ruled nations who had banded together to conquer the world, were ultimately defeated by an international group of superb scientists, many of whom, like Lise Meitner and Enrico Fermi, had been driven out of their countries because Hitler alleged they or their families were ethnically inferior!

After WW-II ended in 1945, vigorous development of nuclear *power reactors* (not to be confused with weapons!) occurred worldwide for the purpose of generating electric power by converting fission heat → steam → electricity. Today uranium produces 21% of all electricity in the USA, 85% of all electric power in France, and close to 50% of all electric power in Japan. Other countries like China and India are quickly following. Clearly the latest and today's most valuable energy resource is:

Uranium and **Thorium**, starting around 1950.

Aside from electricity, so-called "research" reactors produce special "radioisotopes" used in thousands of hospitals by physicians specialized in nuclear medicine. The radioisotopes are tagged onto special pharmaceutical agents used for diagnostics or for therapeutic cancer-fighting applications. Radioisotope-tagged molecules are also used widely as tracers in biotechnology and pharmaceutical research, revealing biological processes and the effects of experimental drugs in the human body. One popular medical radioisotope used in diagnostics is Molybdenum-99 (Mo-99), which is chemically extracted from uranium fission products. Mo-99 decays in 67 hours to radioactive Tc-99m (Technetium-99m) which in turn decays in 6 h to virtually stable Tc-99 with the emission of a gamma-ray (0.140 MeV). The radioactive Mo-99 is shipped in shielded canisters ("cows") that can be filled with saline that extracts ("milks") the short-lived Tc-99m but not the Mo-99. After saline extraction, the Tc-99m is bonded to a bio-organic molecule and injected into a patient's bloodstream. This molecule is designed to be absorbed by certain internal organs whose image and condition is then revealed on an X-ray photo via the emitted 0.140 MeV gammas. The 6-h half-life of Tc-99m insures this element is no longer active for more than a day and easily excreted.

Another application of nuclear power is to use its dumped heat for the desalinization of seawater (California) or for mass urban heating (Mongolia). In the electricity-generating steam cycle, about two thirds of reactor heat is dumped at a lower temperature (see footnote 3 of Chapter 1). This can be profitably used for other applications.

3.4 Summary of Primary Energy Sources

Natural prime energy sources are either "renewable" or "non-renewable". Non-renewables are extracted from the earth with energy expenditures that are a fraction (~50% or less) of the potential heat of combustion possessed by the energy source. However because there is only a finite supply, they are depletable. Renewable energy on the other hand is assumed to be always available. Thus natural primary energy sources can be divided into two catagories:

1. *Non-renewable sources*
   (a) Fossil fuels: oil, natural gas, coal
   (b) Nuclear fuels: uranium/thorium, deuterium
   (c) Geothermal energy: heat pockets
2. *Renewable sources*
   (a) Sunshine (Solar Energy)
   (b) Wind energy
   (c) Water falls (hydro energy) and tidal waves

Energy sources can also be classified as portable or fixed. Of energy sources (1a) through (2c), only item (1a), oil, natural gas, or coal, are portable and can be taken

along in an automobile, truck, or airplane to power it. Refined oil yields portable petrol (hydrocarbon mixtures rich in octane (C_8H_{18})) as well as portable diesel (crude oil distillates with higher boiling point), both of which are liquid at room temperature. Natural gas (natgas) contains mostly methane (CH_4) but also fractions of ethane, propane, butane (C_2H_6, C_3H_8, C_4H_{10}). As mentioned, liquified (111 K) or compressed (~120 atm) in portable high-pressure tanks, natgas can fuel car engines. Coal can of course be carried along as lumps and be burnt to make steam that powers a steam engine as was done in the 1800s. But today most coal and natgas resources are burned in power plants to provide super-heated steam that generates electricity via a turbine (Chapter 6).

Regarding item (1b), nuclear powered ships and submarines have been built and nuclear rockets or aircraft are feasible, but it is not practical nor safe for automobiles to carry nuclear reactors under the hood. Nuclear fission power to propel aircraft and rockets has not been implemented because of problems arising in potential crashes. Electric-grid energy, whether produced by uranium, coal, or other means, is clearly not in a portable form that can be carried by surface vehicles or aircraft as a replacement for petrol, when oil and gas are gone. However electric-grid energy can be converted into portable synfuel energy, as discussed in Chapters 5, 6 and 9. In large cities and parts of Europe, electric trains have been developed that use (nuclear) electric energy from the power grid by means of sliding blades that contact bare high-voltage overhead wires or ground-level trenched conductors.

The harvesting of renewable solar and wind energy is primarily useful in remote locations that need electric power. Assuming wind is available, wind turbines can provide 1 to 2 MW(e) peak power per turbine at an installation cost of about $1 million/MW(e) in 2005 dollars. Solar power may be useful in desert regions, but installation and maintenance costs of solar stations with energy storage systems are quite high even though prices of solar cell arrays have come down considerably in the last 20 years. Of course winds are not always blowing and the sun is not always shining, which limits the use of solar and wind energy in many parts of the world. To replace petro-fuels exclusively with solar and wind energy was reviewed in Section 1.4.2. Chapter 4 discusses the possibilities and limitations of renewable energy sources (2a), (2b), and (2c) listed above in some detail.

For transportation applications, wind-powered sailing ships have of course been used for millennia, while sail-driven or solar-cell-powered cars have been built and do exist. Today these are great for sports but they could not replace the combustion engine to run bulldozers, trucks, cars, or any mass transportation vehicles. One finds in general that solar and wind energy, while attractive, lack sufficient power density to compete with modern compact high-power engines and fuels, and with nuclear power generation. High-density power generation lowers capital costs immensely compared to costs of large-foot-print systems like solar and wind.